SCIENTIFIC APPLICATIONS OF GPS ON LOW EARTH ORBITERS

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Abstract The GPS flight experiment on TOPEX/Poseidon marks the first opportunity to demonstrate the high accuracy and cost effectiveness of GPS-based precise orbit determination for low Earth orbiters, Onc year into the experiment, GPS has delivered orbit accuracies surpassing the best of the conventional ground-based tracking systems, DORIS and satellite laser ranging, and at a far lower cost. A radial RMS orbit error of <3 cm has been achieved by exploiting the unique observing strength of GPS to provide an optimal synthesis of dynamic and geometric information in a technique known as reduced-dynamic tracking. Orbits of this accuracy are now produced daily by an automated data analysis system requiring almost no operator intervention, Because the reduced-dynamic technique is partly geometric, its accuracy will degrade little at lower altitudes. Future topographic and gravity recovery missions such as TOPSAT and GAMES will be able to achieve RMS altitude accuracies of 5 cm or better at altitudes as low as 300 km.

INTRODUCTION

The successful GPS flight experiment on the NASA/CNES TOPEX/Poseidon mission signals a changing order in precise orbit determination (POD) of low Earth orbiters (LEO) (Bertiger et al., 1993; Melbourne et al., 1993; Schutz et al., 1993; Yunck et al., 1993). GPS based tracking promises not only higher orbital accuracy but significant cost reductions as well, through extensive automation of the tracking data acquisition and data processing subsystems. This has already led to a reduction in the workforce requirements for GPS well beyond what has been feasible with ground-based satellite laser ranging (SLR).

We will review the GPS experiment on TOPEX/Poseidon and consider its implications for proposed future missions that will fly in a more onerous dynamical environment (e.g., at lower altitudes). We will then describe some of the more promising scientific applications that will use GPS for high accuracy position and velocity determination, such as TOPSAT, and for geopotential recovery, such as Aristoteles and GAMES; and some lower cost mission opportunities. Finally, we consider the use of GPS on an LEO for recovery of atmospheric temperature and pressure profiles using the radio occultation technique. We also note in passing but will not discuss here the expanding role of GPS in support of airborne missions for topographic mapping and for charting magnetic and gravity anomalies.

THE GPS FLIGHT EXPERIMENT ON TOPEX/POSEIDON

TOPEX/Poseidon was launched on 10 August 1992 (Fu et al., 1991). After a decade of preparation, the GPS precise orbit determination (POD) experiment on TOPEX/Poseidon is now yielding definitive results, The principal limitation of past satellite altimetry missions to study ocean circulation has been the error in determining the geocentric radial position of the altimeter, which was provided by POD with tracking data from ground-based Doppler or SLR. The best Seasat orbits, for example, had a radial accuracy of about 40 cm RMS. Although that can suffice for regional and ocean variability studies, for global circulation decimeter accuracy or better in the radial component is needed. To improve POD accuracy, the TOPEX/Poseidon Project raised its planned orbit altitude from 800 to 1336 km, reducing drag and gravity perturbations, and selected two operational precise tracking instruments—SLR and the CNES-sponsored DORIS Doppler system

(Nouel et al., 1987; Cazenave et al., 1992), 1(also supported extensive development of the ground segments of those tracking systems, and the improvement of spacecraft dynamic models, including the non-conservative forces acting on the spacecraft and the geopotential model. The Project also chose to carry a GPS flight receiver as an experiment and to support the implementation of a global GPS tracking network.

It is now clear from the performance of the two altimeters carried by TOPEX/Poseidon that reducing POD errors below 3 cm RMS would be a major contribution to the determination of sea surface topography and would effectively eliminate POD as a principal error source. We believe that all three tracking systems on TOPEX/Poseidon have performed exceptionally well because of the precautionary actions and tracking system developments undertaken by the Project. The evidence in hand suggests that the SLR and DORIS systems, particular y after tuning the geopotential model, are achieving 4-5 cm RMS in the radial component of the orbit with some residual (-3 cm) geographically correlated error remaining (Christensen et al., 1993). The reduced-dynamic POD strategy with GPS data, we believe, is delivering a radial accuracy better than 3 cm RMS (Bertiger et al., 1993).

The GPS experiment on TOPEX/Poseidon was conceived in the early 1980s by a group at JPL seeking alternatives to conventional Doppler and SLR tracking that would break through the accuracy limitations faced by those systems when applied to low altitude satellites. With the high precision of today's altimetry measurements, ocean science would benefit from centimeter-level orbit accuracies. But traditional POD techniques, which depend on precise models of satellite forces to recover the orbit, are limited by imperfections in those models, which grow large at lower altitudes. JPL therefore turned to geometrical techniques, which are insensitive to dynamical limitations, and soon realized that the enveloping coverage given by GPS offered an almost ideal solution. By the mid-1980s, a strategy known as reduced-dynamic tracking emerged (Wu et al., 1991) that sought to combine the best elements of dynamical and geometrical positioning to minimize overall orbit error. This POD technique has been applied to TOPEX/Poseidon to yield the above-cited orbit accuracies.

The GPS Tracking System. The GPS tracking system consists of four segments: the GPS constellation (Fig, 1), the flight receiver (Fig. 2), a global network of GPS ground receivers (Fig. 3), and a central monitor, control and data processing facility (Fig. 4). The POD strategy requires continuous tracking of the visible GPS satellites by ground and flight receivers, Data from all receivers are brought together and processed in a grand least squares solution in which the TOPEX/Poseidon orbit, all GPS orbits, receiver and transmitter clock offsets, ground station coordinates, Earth rotation, and other parameters are estimated. Simultaneous sampling at all receivers (which may be achieved by later interpolation) eliminates common errors, such as clock dithering from GPS selective availability and clock instabilities in the receivers. The orbit information of TOPEX/Poseidon is expressed in a reference frame established by key sites in the global GPS tracking network, known to about 2 cm in the International Terrestrial Reference Frame (Boucher and Altamimi, 1993). The GPS satellite orbits and terrestrial reference frame transformation parameters are also improved (over current results obatined from the ground network alone) by including TOPEX flight data,

The Global Positioning System. Fig. 1 illustrates the GPS constellation, also known as the space segment, which consists of 24 GPS satellites in 12-hr (20,200 km altitude) circular orbits (Milliken and Zoner, 1978; Spilker, 1978). The satellites are distributed in six orbit planes inclined at 55° to the equator. Each satellite broadcasts navigation signals on two L-band frequencies, 1.57542 GHz (L1) and 1.2276 GHz (L2), coherently derived from a common clock oscillator at 10.23 MHz through multipliers of 154 and 120, respectively. The corresponding carrier wavelengths are approximately 19 and 24 cm. The beamwidths (3 dB) of the GPS signals extend roughly 3,000 km beyond the limb of the earth as viewed from the GPS satellites. At any point on the Earth's surface, or in the space below 3000 km, typically 5 to 9 GPS satellites are continuously visible within a

vertically centered hemispherical field of view. Each L-band carrier is modulated with a precise pseudorandom ranging code, known as the P-code, that enables the receiver to determine precisely and unambiguously the arrival time of each code bit, Since the transmission time (as kept by the GPS satellite clock) is known, this measurement determines the range plus the time offset between the GPS satellite and receiver clocks, a quantity known as the *pseudorange*. The L1 signal is also modulated in quadrature (90° out of phase from the P-code) by a less precise ranging code known as the coarse/acquisition code, or C/A-code. Finally, both L-band signals are further modulated by a 50 bit/see data message, which provides accurate GPS orbits, GPS satellite clock offsets from a time standard known as GPS time, GPS satellite health status, and other information of value to the user.

Although we often think of the pseudorange measurement obtained by tracking one or more of the ranging codes as the fundamental GPS data type, a receiver that is tracking a code can also continuously measure and count the phase of the L-band carrier on which the code is imposed, This enables the receiver to provide Doppler (range rate) and integrated Doppler (range change) data and thus velocity and position change solutions as well. Because the carrier frequencies are 100 to 1000 times the bit rates of the ranging codes, carrier phase measurements are 100 to 1000 times more precise than pseudorange measurements. Dual frequency observations permit nearly perfect correction of the ionospheric delay, which is the sole reason for providing the second frequency. Typical 1 sec measurement precision are 20 cm for pseudorange and 0.2 mm for phase with the best commercial GPS receivers, though bear in mind that a raw phase measurement contains an unknown initial phase bias while pseudorange measurements are absolute. For precise satellite orbit determination and baseline (or vector) measurements between receivers, carrier phase is the fundamental observable.. The information content in the measurement is range change (integrated Doppler without cycle breaks) over the satellite pass.

The GPS Flight System. Fig. 2 is a line illustration of the pair of Monarch™ GPS receivers located in the TOPEX/Poseidon spacecraft, Fig. 4 shows the location of the GPS antenna atop a 4.3 m mast on the TOPEX/Poseidon spacecraft, which is needed to avoid reflected signals from the TDRS high-gain antenna and other surfaces such as the solar panel, The Monarch GPS flight receiver [Carson et al 1988] was developed by Motorola for TOPEX/Poseidon under contract from JPL. Each receiver weighs 6.8 kg and consumes 29 w of power. It tracks up to 6 GPS satellites concurrently and measures the phase of both carriers at 1-see intervals and P-code pseudorange at 10-sec intervals. Random phase errors at l-see sampling are less than 2 mm; systematic errors are less than 5 mm. Phase center variation of the antenna with elevation and azimuth angles was measured prior to launch and is known to better than 5 mm. Our confidence in the accuracy of the reference position of the phase center relative to the spacecraft center of gravity (cg) is somewhat tentative; although a pre-launch determination of this offset vector was made with supposedly sub-centimeter accuracy using direct measurements and a spacecraft model for the cg location, daily POD results over the past year consistently require a correction of 5-6 cm with an uncertainty of less than 1 cm. The origin of this discrepancy is under study. The actual cg location is somewhat variable at the sub-centimeter level because of the changing spacecraft configuration in orbit.

The GPS Global Tracking Network. Only about a dozen globally distributed ground sites, which are shown in Fig. 3, are needed to obtain full accuracy because the satellite's orbital motion provides ample flight/ground covisibility of the GPS satellites. For ground programs (which achieve a weekly geocentric station location precision of about 1 cm), 20-40 sites are generally required (Blewitt et al., 1993), These sites are part of the larger global network currently being implemented and operated by an international consortium of organizations under the IAG-sponsored International GPS Service, which provides very accurate tracking and POD products for scientific applications (Neilan and Nell, 1993).

The GPS Operations Center. All transactions involving GPS data and POD products flow through the operations center (Fig. 4), which automatically retrieves data from all GPS sources—about 8 Mbyte/day from the flight receiver and 1 Mbyte/day from each ground site. The center monitors and controls the ground and flight receivers and initiates actions to repair system faults. The ground receivers can store their data for, in most cases, up to 12 days to protect against communication outages. In the first 6 months of experimental operation we acquired 99% of the possible data from the flight receiver when GPS anti-spoofing (P-code encryption) was turned off, and approximately 95% from the ground receivers. Precise orbits from GPS are now produced with 30-hr data arcs on 24-hr centers, providing 6-hr overlaps for orbit comparisons. Precise orbits and statistical quality measures are available to analysts about 8 hrs after all data for 1 day are received. Release of the orbits occurs about 1 wk after the end of each 10-day orbit repeat cycle.

Alternative POD Strategies, The extraordinary tracking coverage provided by GPS allows one to consider alternative POD strategies. The radius of a GPS satellite orbit is about 4.1 times the radius of the Earth and the orbital inclination is 55 deg. About a third of the global constellation is in view above the local horizon of an LEO; typically 5-9 GPS satellites are in view in this hemisphere, and sometimes as many as 11. The Monarch receiver, which has only 6 channels, on average tracks about 5.7 GPS satellites continuously. Future GPS flight receivers should provide "all-in-view." tracking. Fig. 1 illustrates the three-dimensional and continuous nature of the GPS tracking system measurements. The figure also shows the wide GPS covisibility by the flight and ground receivers, which permits elimination of satellite and receiver clocks as an error source.

GPS provides a geometric data strength unrivaled by any other system. SLR, for example, provides highly accurate one-dimensional measurements (slant range) during short intervals (10- 15 rein), but large coverage gaps remain, This observational weakness must be overcome with precise models of all forces acting on the spacecraft. In a few regions (e.g., North America, Europe), two or more SLR systems can range to the satellite concurrently, which when difference provides cross information as well as slant range. But these cases are rare and do not relax the requirements for precise dynamic modeling. The same situation will apply to PRARE once it is successfully deployed, DORIS, with its 40-50 station ground network provides more coverage but it uses an inherently weaker range rate scalar measurement (carrier phase change over 9 see) and its current implementation allows it to interrogate only one ground station at a time. DORIS also requires precise dynamic models. GPS, by contrast, provides a continuous 3-dimensional position change vector from the carrier phase measurements and will do so as long as the receiver tracks; this gives the analyst new options for reducing POD errors arising from deficiencies in the spacecraft dynamic and measurement models.

Full Dynamic POD. In a full dynamic approach the orbit solution is strongly constrained by dynamic models. Deficiencies in those models, if unaccounted for, can result in magnified POD errors in components of the state vector that are weakly observed. Judicious least squares adjustment of empirical (e.g., once-per-revolution) global force parameters to relax the grip of the model errors is still considered fully dynamic. More frequent local relaxation along the orbit with sparse tracking data may greatly increase POD error because of the limited observability provided by the tracking system. Thus, SLR and DORIS are restricted to a full dynamic POD strategy because of their incomplete coverage and limited observability.

Reduced-Dynamic POD. With GPS one can approach a pure] y geometric solution and lessen the influence of force model errors, by adding to the dynamic model a 3-D stochastic acceleration vector that is re-estimated (subject to stochastic constraints) at each time step (e.g., every 5 rein). Each component is characterized as a first-order Markov process on which *a priori* constraints are imposed by specifying its variance and correlation time. The procedure is to introduce these stochastic vector series into the TOPEX/Poseidon dynamic model after a converged full dynamic POD solution is obtained. (For the GPS satellites an

essentially full dynamic POD approach is retained because of the limited observability from ground-based observations and the relatively benign dynamics at the GPS altitude.)

Because the GPS observing geometry is so consistently strong, the constraints imposed on the stochastic acceleration vectors can be greatly relaxed. When that is done, a least squares adjustment of the local accelerations must rely more on geometry and measurement accuracy than on dynamics. In the extreme, where the stochastic constraints are lifted (zero correlation time and infinite variance), the least squares solution essentially becomes purely geometric. Reduced-dynamic POD attempts to optimize the result by choosing the stochastic constraints to balance dynamic error against geometric limitations— to draw the best from both the models and the measurements (Fig, 5). Dynamic model errors still appear but at a diminished level that depends on the stochastic constraints. If, however, the aim is to improve the gravity field, the stochastic vector estimate must be inhibited so the dynamic model is strongly determined. Ultimately, the best GPS-based orbit solutions will come from a dual approach (Yunck et al., 1993; Schutz et al., 1993) that strives to improve the dynamic models and the measurement system.

For TOPEX/Poseidon a purely geometric solution is inadvisable. The Monarch receiver can track only six satellites at once, and the current onboard satellite selection algorithm (which can be modified) holds the effective field of view to less than a hemisphere, limiting geometric strength (i.e. degrading the PDOP). Experiments show that radial accuracy falls to 12-15 cm with a nearly geometric solution, Covariance studies indicate, however, that an all-in-view receiver with a full sky field of view could provide geometric POD accuracies of <5 cm (Wu et al., 1991).

Analysis Results. For a new technique such as GPS-based POD that is posited to have unprecedented accuracy, one faces the dilemma of establishing standards for comparison that are credible; results using such standards necessarily will be compromised because their error or noise sources are likely to be larger than those of the technique being tested. The analysis team has assessed GPS-based POD performance using several measures. Some of these are measures internal to the GPS tracking system such as postfit residuals, formal errors of the POD solutions from their least squares covariance matrices, agreement of orbit overlaps, and comparison of reduced-dynamic and full dynamic solutions. Other measures are external such as comparison with SLR and DORIS dynamic solutions, and altimeter closure and crossover agreement. From these tests we have concluded that the GPS-based POD is routinely providing satellite altitude with an RMS accuracy of better than 3 cm. Recent tests also indicate that -5 cm accuracy is being achieved in the along-track and cross-track components. A detailed discussion of these results will be found in Bertiger et al. (1993). Here we have selected three key tests that bear on radial accuracy.

Postfit Residuals. As one of the quality checks, the postfit reduced-dynamic residuals on the ionospherically calibrated carrier phase measurements over the full arc are examined. Anomalous data points are automatically detected and removed, In general, the phase residuals for the flight receiver have an RMS value of less than 5 mm and reveal little or no systematic signatures; this is nearly equal to the combined receiver phase data noise and multipath error. This implies no substantial mismodeling in the estimation process. On the other hand, the full dynamic GPS solutions show postfit residuals of about 1.2 cm RMS overall and show systematic signatures that are geographically correlated, suggesting that noticeable error remains in the geopotential model (JGM-2) used in the dynamic solution. The GPS data are in general of high quality; only 0.01% of data are detected as anomalous and automatically removed from the filtered solution.

Overlap Agreement. The reduced-dynamic solutions are performed daily with 30-hr arcs of data. Thus, each day's solution is derived from a largely independent data set and provides a 6-hr common overlap with its neighbors for orbit comparison (Fig. 6). Fig. 7 shows the RMS altitude agreement over the central 4.5 hrs for twelve complete 10-day cycles spanning about five months and centered in mid-May 1993. (Reduced-dynamic solutions are susceptible to "edge effects" over the last -45 reins of the arc because of the

lack of data past the edge to constrain the stochastic accelerations.) The RMS agreement is consistently below 2 cm, with an average of about 1 cm. The overlaps with reduced-dynamic filtering are consistently better than those with dynamic filtering, which have an altitude overlap difference as high as 5 cm RMS, with an average RMS of about 2 cm.

Since the data are identical on the overlaps and the reduced-dynamic solution is partly geometric (i.e., local), a principal cause of the discrepancy is the error in the GPS orbits. The GPS orbits are determined dynamically over each 30-hr arc and will disagree on the overlaps because their solutions are substantially influenced by non-common data compounded by dyamic mismodeling. The GPS orbit discrepancy will then appear in the TOPEX/Poseidon overlap comparison, but scaled down by approximately 20:1 because of the common mode error cancellation between the flight and ground receivers. Fig. 7 shows that the overlaps were best during Cycle 19, a 10-day interval in May 1993 when all of the GPS satellites were out of the eclipse season. The GPS constellation is eclipse-free about 12% of the time and a single orbit plane (containing 4 GPS satellites equal] y spaced in true anomaly) is in eclipse about half the time. The complex dynamics of eclipsing orbits (and our limited dynamic and observational models for the GPS satellite during eclipse and during ingress and egress of the Earth's shadow cone) generally degrade GPS orbit accuracies and hence the TOPEX/Poseidon overlap agreement.

In view of the importance of GPS orbit errors in the overlap comparisons, the overlap test, contrary to one's usual expectation when common data sets are involved, is probably a fairly reliable measure of the relative quality of the TOPEX/Poseidon 30-hr orbits.

Crossover *Analysis.* An external method for assessing orbit accuracy in the radial component relies on radar altimeter data collected by TOPEX/Poseidon. The ionospherically corrected range measurements from the dual-band altimeter have an instrumental accuracy of better than 4 cm. These radar measurements can be used together with the precise radial position of TOPEX/Poseidon to determine the geocentric height of the sea surface. At the points in the ocean where the satellite ground tracks intersect on ascending and descending passes, two such determinations of sea height can be made. In the absence of errors in the radial component of the orbit and in the media corrections to the altimeter range, the height difference at the crossing point location is a measure of the true variability of the ocean surface. On the other hand, true variation at a crossover point will mask the orbit errors and complicate their assessment,

Crossover observations with the NASA dual-frequency altimeter from eight 10-day repeat cycles of the TOPEX/Poseidon ground track were used to evaluate orbit errors. The details for this analysis are found in Bertiger et al. (1993). All standard environmental and sea-state corrections were applied and editing was performed based on the data flags provided with the crossover geophysical data records (GDR). As crossovers may occur days apart, tidal corrections were applied. Unmodeled sea height variation from changes in ocean currents was minimized by restricting the analysis to crossovers that occur within the individual cycles. The table below (from Bertiger et al., 1993) lists the global crossover statistics for the GPS reduced-dynamic orbit and fen- the two precise orbits provided with the merged TOPEX/Poseidon GDR products, The NASA precise orbit was generated by GSFC using SLR and DORIS tracking and the tuned geopotential field known as JGM-2

Altimeter Crossover Statistics

Orbit	Number	Mean (cm)	RMS (cm)	Var (cm^2)
GPS Reduced Dynamic	36403	*-0.04*	*9,69*	*93.84*
NASA Precise Ephemeris	36403	0.35	10,22	104,41
CNES Precise Ephemeris	36403	1.04	10.13	101.47

(Lerch et al., 1993); similarly, the CNES orbit was generated by the CNES/Toulouse group using DORIS and SLR tracking. Both use a full dynamic estimation strategy. Over 36,000 individual crossovers occurring in the period from January 30 to May 19, 1993, are represented in the global statistic.

The actual radial orbit error is difficult to quantify based on these statistics since the residuals also contain errors in the media corrections, and unmodeled oceanographic effects. A large portion of the tidal and atmospheric pressure signal has been removed with global models, but a sizable signal remains. In order to address this difficulty, a small number of crossovers from the original global data set have been separated using a highly restrictive set of geophysical editing criteria that eliminate points where one or more of these criteria are violated (Bertiger et al., 1993). These include regions with large sea state variability, tidal model uncertainties, high wind speed, etc. Application of these criteria is designed to significantly reduce unmodeled ocean variation, while still maintaining a global distribution of data. To the extent that the geophysical and environmental corrections being interrogated are not correlated with the orbit error, this approach should help to isolate the orbit error contribution.

The table below lists the global crossover statistics for the data remaining after application of the restrictive editing criteria. It is important to note that the editing was rigrously performed "in-the-blind"; only after applying the editing criteria were the remaining cross-over residuals re-examined. None of the cross-over points was eliminated on the basis of outlier consideration because the outlier residual might have been due to excessive orbit error, While only 3% of the original data remain, there are still over a thousand globally distributed observations. The variance (energy) has been reduced by over 50%, corroborating that the statistics of the' original data set reflect primarily contributions from non-orbit sources. Assuming that the residual variabilities are uncorrelated in a global sense on ascending and descending tracks, one could infer that the radial orbit error is less than 5 cm RMS $(7/\sqrt{2})$ regardless of the orbit solution under consideration. Contained in this figure is some residual error from the geophysical corrections and instrumental effects, as well as orbit error. On the other hand, if there are large stationary orbit errors that are highly correlated on ascending and descending passes—an extreme example is an error in the overall scale of the orbit—then the crossover observations cannot observe them,

Despite these caveats, the crossover statistics provide a powerful and independent tool for measuring orbit consistency and for gauging improvement. In this context, we note that the GPS-based reduced-dynamic orbits yield the lowest crossover residuals with a variance that is about 10 cm^2 lower than that obtained by the other tracking techniques, suggesting that the GPS orbit results in an improved representation of the actual TOPEX/Poseidon orbit. If the proper interpretation of the overlap data is that the GPS reduced-dynamic solutions are accurate to 3 cm, then the table below suggests that about 5 cm of noise remains in this set due to altimeter noise, residual errors in the environmental and geophysical corrections, and ocean variability. This would also suggest that the NASA and CNES precise orbits are accurate to about 4-5 cm, which in itself signals the remarkable progress in POD in general that has been accomplished with TOPEX/Poseidon.

Altimeter Crossover Statistics for Restrictive Editing Approach

Orbit	No.	Mean (cm)	RMS (cm)	Var (cm^2)
GPS Reduced Dynamic	1233	0.32	6.16	37.85
NASA Precise Ephemeris	1233	0.68	6.86	46.56
CNES Precise Ephemeris	1233	1.92	7.03	45.68

OPERATIONAL STATUS OF THE GPS TRACKING SYSTEM

Availability & Reliability of the System. For an experimental system which started operations on 2 November 1992, the overall availability has been surprising y good, Each element of the system has different operational reliability characteristics.

The GPS Constellation. The constellation increased from 17 to 25 satellites during the first year of the mission. Early in 1994 the constellation will stabilize at 24 Block 11 satellites. For precise tracking the GPS constellation is fully operational and has provided complete global coverage of low Earth orbiters since reaching a size of -18 satellites, The principal limit to system availability has been the use of the GPS Anti-Spoofing function, In addition, the constellation occasionally produces anomalous transmissions that have resulted in flight receiver outages, as discussed below.

The Flight Receiver, The Monarch receiver requires an initial upload from the ground to load ephemerides and to set the receiver clock. Once initialized, it is designed to operate autonomously, using TOPEX/Poseidon position solutions and GPS broadcast ephemerides to aid GPS acquisition, The receiver calculates GPS view periods, and up to six satellites are chosen based on length of track, mutual visibility with ground stations, and geometric strength. If 6 GPS satellites are not available, the receiver assigns multiple channels to track the same satellite for engineering test purposes. On a typical day, each channel is locked to a satellite 98% of the time, with the remainder spent in the acquisition mode.

The reliability of the flight receiver is still being proven. Reasons for flight receiver data outages are summarized in the table below.

Monarch Flight Receiver Data outages (372 day sample beginning 2 Nov, 1992)

Cause	Days (nearest whole day)	Percent
Anti-Spoofmg ON	31	8.3%
GPS Constellation Anomalies	24	6.5%
SEU's	2	.5%
Receiver stopped to change Parameters or Software	2	.5%
Total	59	15.8%

The Monarch receiver has required operator intervention more often than had been expected, When automatic receiver operation fails, operator action is needed to restart it. The receiver can cease to operate automatically if the onboard state vector is corrupted or if flight software execution is interrupted by a radiation-induced single-event upset (SEU).

There has been only one case where automatic receiver operation was interrupted by an SEU—a memory location containing flight software was upset, The problem was corrected by reloading the software from the ground, and 2 days of data were lost, An SEU-induced anomaly is difficult to distinguish from a hardware failure. A methodical approach to recovering from these events is being taken to make sure we understand the reason for the anomaly, The microprocessor and other digital circuitry are also somewhat vulnerable to SEUs. We had estimated the mean time between events that would upset automatic operation of the receiver at -3 years. We do not yet have enough experience to know if that level of performance will be realized.

Shortly after launch we noticed that the GPS satellites were broadcasting bad data on a fairly regular basis. The flight receiver has detected values of pseudorange that were in error by millions of kilometers, ephemeris data that were incorrect by a large fraction of an orbit, ephemeris dates that were incorrect by several months, and ephemeris messages corrupted by SEU's on the GPS satellite, The U.S. Department of Defense (DoD) policy regarding GPS integrity requires that its GPS Control Segment take prompt action to

correct these anomalies. Their response time has been between 1 and 5 hrs. However, the Monarch receiver scans the entire GPS constellation within the orbital period of TOPEX/Poseidon, 1 hr and 52 min. It is difficult for the flight receiver not to encounter these anomalies when they occur, We have therefore built traps into the flight software that prevent anomalous data from corrupting the onboard navigation solution. When an anomaly is trapped it is also reported in telemetry. Anomalies have occurred approximately once every 20 days. Most of these are now being trapped and do not affect receiver operation, If the receiver fails to trap an anomaly and shuts down, restarting involves uploading an accurate state vector and commanding the receiver to the autonomous mode of operation. Anywhere from 6 to 36 hrs of data can be lost due to these incidents.

Because of its vulnerability to anomalies, we check the receiver several times per day. Telemetry data are available in two modes: real time, and playback. About 50% of the time the TOPEX Ground System (TGS) has a real time link to the satellite through TDRSS, allowing the flight receiver operator to monitor the decommutated data from the receiver as they are being acquired. This can be done from anywhere over telephone lines. GPS flight receiver data destined for the POD teams are assembled from the playback of telemetry from the flight tape recorders. These playbacks occur at 8-hr intervals and take -15 min. Data from the flight receiver are delivered from the TGS to the GPS POD team in daily batches. Data for a given day are delivered by 05:00 UTC the following day.

The entire GPS flight assembly on the Topex/Poseidon spacecraft - twin receivers, mounting plates, antenna, and boom - weighs 29 kg and consumes 29 watts of power. Motorola plans to significantly upgrade the Monarch for the Geosat follow-on mission. All of the hi-polar digital circuitry in the receiver will be replaced with CMOS; the receiver should weigh less than 2.3 kg and use less than 12 watts.

The GPS Global Network. Special attention, has been given to keeping the stations supporting the TOPEX/Poseidon GPS experiment operating, Most of these stations have full-time staff to support functions other than GPS. But complete on-site sparing was a luxury inconsistent with the limited scope of the experiment. Instead, one spare receiver was held in reserve at JPL. In spite of the limited commitment to guaranteeing availability, overall data return from the 12-14 stations used in the experiment has exceeded 95%.

The Network Monitor and Control, All receivers in the network can store data for up to 12 days, so if communications are down on a given day, the data for that day can still be retrieved. This does, however, require action by the network operators. Early in the mission we lost several days of data from a ground station because of an operational error at the monitor and control center. No data have been lost for that reason since then.

Automation of the Processing Facility. Data acquisition and editing, precise orbit production, and orbit validation are almost fully automated. An analyst checks the results for accuracy and completeness and decides whether reprocessing is needed. The automatic system yields deliverable products without operator intervention approximately 80% of the time. About 16% of the time processing is interrupted by a computer system malfunction. About 3% of the time an error in public reports regarding a GPS maneuver (e.g., the wrong date) has necessitated reprocessing. The precise orbits can be delivered to users within 5 days of data acquisition. The principal reason for the lag is the delay in getting data from all ground sites. The delay from each site depends greatly on the mode of communication and ranges between a few hours and several days, In an operational mode it would be straightforward to achieve and reliably maintain a data latency from all sites of no more than a few hours. Once the data are available the processing for a single day is completed within 6 hrs. This usually occurs at night and the results are available when the analyst arives in the morning. If there have been no problems, the product is ready to use at this point—hours after the last ground data became available for processing. Since the overlap statistics are an important measure of the quality of the orbit estimate, we hold the orbit until it is tested against the succeeding day's solution.

Validation and Quality Assessment of the Orbit Estimate Product. Validation of the GPS-based orbit estimate is extremely robust. The data are checked for internal consistency

by means of the coherence and group/phase relationship between the carrier data and the pseudorange. The residuals of the fit are computed first for the dynamic solutions for both the ground and flight receivers and again for the reduced-dynamic solution. The resulting GPS satellite orbit and Earth rotation solutions are compared against those same solutions produced by JPL for the International GPS Service without flight receiver data. In general, solutions that include the flight data are more accurate by up to a factor of two. Finally, the RMS overlap statistic is computed for the both the dynamic and reduced-dynamic solutions to ensure that system problems are detected before delivery to users.

Recurring Costs for an Operational GPS POD System. The GPS experiment has demonstrated that the production of operational precise orbits with GPS will be significantly cheaper than with any of the tracking alternatives; fewer ground stations and people are required. Extensive automation in data handling and synergy with related NASA Earth Science and Space Communications programs have kept the recurring costs of GPS tracking and the marginal cost to support an additional mission exceptionally low. The table below provides our estimate of these costs for future applications,

Resources Requirements: Recurring Cost Factors

Cost Element	Recurring Costs for the First Mission. (workyears and US$)	Marginal Cost to Support an Additional Mission at the same time
Management	0.5 Wy	0.1 wy/yr
Flight Receiver	0.5 Wy	0.1 wy/yr
Global Network of GPS Ground Receivers	0.4 wy	Nominally zero for POD. But could depend on other mission specific needs.
Network Monitor & Control	1.3 Wy	ditto
Data Acquisition	0.8 wy	ditto
Data Processing	1.5 wy	0.5 wy/yr
Computer Maintenante	50 K	
Travel & Support Services	40 K	
Total	5.0 person + $90K/yr	< 1.0 wy/yr

In summary, the recurring cost for performing GPS-based POD on a single LEO is around US$850K/year and the marginal cost for adding another mission is -$150K/year.

Flight Receiver Procurement and Integration Costs. The cost of a flight receiver (and ground support equipment) depends strongly on reliability requirements and wherein the development phase the receiver is procured. For example, the cost of procuring the second Monarch receiver *at the same time as the original procurement* (i.e., common parts buy and qualification program) was less than 10% of the cost of the original. (TOPEX/ Poseidon has redundant flight receivers.) Given that the development has already been done, it likely that the procurement cost for a stand-alone, high-performance flight receiver with Class A reliability (mission critical), plus its ground support equipment and overall systems engineering costs, would be $3-4 M. To this one must add spacecraft integration and launch operations costs, but these will be about the same for all comparable flight instruments with similar functionality and complexity, For a low cost mission with a short nominal life time and low altitude, where increased risk can reasonably be incurred in exchange for lower cost, procurement costs would more likely be $300-400 K.

GPS Security Issues. GPS is equipped with two distinct security mechanisms known as selective availability (SA) and anti-spoofing (AS). SA is intended to deny the highest real time GPS position and velocity accuracies to unauthorized users, while AS prevents the mimicking of GPS signals ("spoofing") by hostile forces. Because we are using GPS in a differential mode, only the second of these has any practical consequences; however, for completeness we shall discuss them both.

Selective Availability. SA consists of two measures to degrade positioning accuracy to the unauthorized user: (1) the insertion of errors into the GPS ephemeris and clock parameters in the broadcast data message, and (2) "dithering," or intentional variation of the fundamental oscillator frequency, which causes the measured phase and pseudorange to vary by tens of meters, Neither of these poses a problem for the differential GPS tracking used for TOPEX/Poseidon. Receiver sampling times can be synchronized so that dither effects are common to all measurements and drop out of the differential solutions. When sampling is not synchronized, quadratic interpolation to a common epoch can still achieve a high degree of dither cancellation provided the sampling interval is no longer than about 10 sec (Wu et al., 1990). GPS ephemeris and clock errors do not come into play since those quantities are solved for with the ground data. SA has been on almost continuously during the TOPEX/Poseidon experiment, with no effect on orbit quality.

Anti-Spoofing. AS is accomplished by encrypting the P-code—that is, changing the code to another code (called the Y-code) known only to authorized users. In the presence of AS, a civil user with a conventional code-tracking receiver would be able to track only the C/A-code, recovering pseudorange and carrier phase on L1 only. This prohibits computation of the standard dual-frequency ionospheric correction. There are, however, several GPS receiver models commercially available that can operate in a codeless or quasi-codeless mode, producing carrier phase and pseudorange at the L2 frequency during AS without knowledge of the Y-code, while tracking the C/A-code on L1. Although L2 codeless data are of degraded precision, the typical codeless phase error of about 0.5 cm in 1 sec is similar to that obtained by the Monarch receiver when AS is off. Phase measurement noise, moreover, is generally not the dominant error in an orbit solution, so orbit accuracy would not be affected by a switch to codeless L2 operation. The L1 phase measurement retains its full precision with C/A-code tracking.

Because GPS-based POD on TOPEX/Poseidon was considered during the planning stage to be experimental, we did not include a decryption or codeless capability in the Monarch receiver; consequent y, the receiver can only recover L 1 phase and C/A pseudo-range when AS is on, and POD accuracy is somewhat degraded. (Early experiments indicate a radial RMS accuracy of 5-8 cm with AS on.) It continues to track the satellite in this mode until that satellite sets; at the same time, it tracks those GPS satellites that have AS off in the P-code mode. NASA had an agreement with the DoD that guaranteed certain periods when AS would be off during 1992-93; NASA is currently re-negotiating with the DoD for future periods of AS-free operation for TOPEX/Poseidon.

For future missions there are two principal options for dealing with AS: (1) become an authorized GPS user and fly a receiver that can decrypt the Y-code, and (2) fly a receiver that can switch to codeless tracking on L2. We will not attempt to resolve this choice here but will make a few observations. Because of agreements that are already in place between NASA and the DoD, the first choice is easily accomplished from an administrative standpoint. Moreover, at least one suitable space qualified Y-code receiver will soon be available commercially (Motorola's Advanced Monarch™, an update of the TOPEX/Poseidon receiver being developed for Geosat Follow-on), while no space-qualified codeless receiver yet exists. Use of a Y-code receiver would, however, impose certain security constraints and attendant costs on mission operations both before and after launch. The cost of security is very specific to the logistical parameters of a given mission.

Recently a proposal was made by JPL to NASA to develop a high performance GPS flight receiver specifically for the precise orbit determination of future NASA missions like TOPSAT, GAMES, Gravity Probe B, and TOPEX Follow-on. Two options were

presented: (1) a version of the Advanced Monarch with decryption, and (2) a new hybrid receiver combining Monarch P-code tracking hardware and existing codeless technology developed at JPL for ground receivers. The latter would have eight dual-frequency channels, compared with six for the Monarch, and would meet all of the requirements of these missions. NASA agreed that a multi-mission receiver is desirable and expressed a preference for the hybrid P-code/codeless option. As yet, however, no firm funding commitment has been made.

FUTURE PROSPECTS FOR GPS FLIGHT APPLICATIONS

While the current altitude accuracy of <3 cm RMS with GPS on TOPEX/Poseidon surpasses our expectations, a number of improvements can yet be made. Innovations in data processing strategies and modeling that are planned for implementation over the next year should further improve TOPEX/Poseidon POD accuracies by a factor of two or perhaps three. These include updating the tidal models and the GPS satellite maneuver and phase center models, adding site- and elevation-dependent data weighting, extending the GPS satellite solution arcs, adding empirical force adjustments to the GPS satellite orbit solutions, and improving the dynamic models for the GPS satellites.

One clear message from these results is that both the dynamic and reduced-dynamic techniques are surpassingly accurate on TOPEX/Poseidon because of its high altitude and extensive dynamic modeling. But future missions at lower altitudes will face a tougher challenge. Below 700 km, atmospheric drag and gravity errors explode and dynamic orbit solutions degrade correspondingly. For example, TOPSAT, a proposed NASA mission that would fly at 560 km while requiring 7 cm RMS altitude accuracy, could not consider a full dynamic approach. Reduced-dynamic tracking can, in principle, sustain few-centimeter accuracy down to the lowest altitudes. Fig. 8 shows the projected POD accuracies for full dynamic and reduced-dynamic POD strategies as a function of altitude, assuming a 12-channel GPS receiver and full sky field of view. (At 800 km a full field of view will see 12-17 GPS satellites continuously above the Earth's limb.)

As we have noted, the TOPEX/Poseidon experiment has demonstrated that operational POD can be cheaper in terms of both ground operations and POD personnel than with any of the tracking alternatives. The automation already achieved in data handling and analysis, and the synergy with various ongoing NASA programs (e.g., deployment of a global receiver network; high volume data analysis) have kept down both the operational costs of GPS tracking for TOPEX/Poseidon and the marginal cost to support additional missions,

Prospects for GPS on Future Missions. Several proposed and planned missions would benefit greatly from use of a GPS-based tracking system. Indeed, ERS - 1 could be enjoying few-centimeter radial accuracy if a GPS flight receiver had been flown, instead of the 15-25 cm radial accuracy now being realized with SLR.

TOPSAT, JPL's twin-spacecraft concept for NASA's proposed TOPSAT mission would use interferometric synthetic aperture radar to map the earth's topography with a spatial resolution of 30 m and a height accuracy of 1-3 m (depending on surface slope) over land, and 300 m resolution with a 10 cm height accuracy over the polar ice sheets. TOPSAT presents three strict positioning requirements that can be met by differential GPS techniques. These include the continuous determination of: (1) the absolute geocentric altitude of each spacecraft to 7 cm RMS, a few days after the fact; (2) the relative along-track component between spacecraft to 10 cm RMS, within 6 hrs; and (3) the 3D vector between the two spacecraft to 3 mm RMS in each component, within a few days, Each of these can be met by exploiting the continuous L-band carrier phase measurements produced by high performance GPS receivers, and the consistently strong GPS observing geometry, That the first two requirements (including latency) can be met has already been demonstrated with TOPEX/Poseidon. As for the third, the separation distance of the TOPSAT

spacecraft is 1-2 km and we know from ground GPS programs that millimeter differential positioning accuracy is feasible at these distances.

GAMES. Another proposed NASA/CNES mission, GAMES is a geopotential mission under study by GSFC for recovery of improved gravity and magnetic information for the earth. It would include scalar and vector magnetometers, a laser ranging system between the primary spacecraft and small, passive subsatellites for monitoring along-track gravity perturbations, an accelerometer for monitoring drag, and a GPS receiver. The accuracy requirement for radial positioning is about 10 cm, However, the continuous carrier phase measurements from the GPS receiver will also reflect gravity perturbations, and would complement the laser ranging data. A proposed ESA counterpart to GAMES, known as Aristoteles, would derive similar benefits from GPS.

A variant on GAMES under study at JPL is a low-cost (probably <$60 M) gravity-only mission in which a pair of identical small spacecraft are flown at an altitude of about 350 km with an along-track separation of about 300 km. The orbits would decay to -150 km within a few months, sweeping through some gravity resonances and enhancing the amplitudes of the tones in the frequency response spectrum of the orbit perturbations. The spacecraft could then be boosted back to their original altitude for a repeat performance. Each spacecraft would carry a GPS receiver, an accelerometer, and a dual-band high-frequency (-25-50 GHz) two-way (or pseudo-two-way) RF links for high-precision along-track phase measurements. Significant gravity information up through wave number 80 should be obtained within the first few months. This gravity mission should effectively solve the ocean geoid problem for oceanographic altimetry missions that study ocean circulation at mesoscale wavelengths and longer. The major requirement on the GPS receivers is that they provide ionospherically corrected carrier phase measurements with sub-millimeter accuracy at a 1-see rate, an easy task for high performance ground receivers today, and one which will be attained with the next generation of flight receivers.

GPS/MET. This is an atmospheric limb sounding mission proposed by UCAR (Ware, 1992) to be flown in 1994 that is based upon the earlier GGI concept proposed by us for EOS (Fig, 9). In this mission the signals from a GPS satellite being occulted by the earth's limb are tracked by a GPS receiver aboard a LEO. As the received signal passes deeper into the atmosphere its amplitude and phase are progressively altered through atmospheric refraction and possibly interference arising from spatial irregularities in refractivity. The signal delay and amplitude profiles recorded by the LEO during the occultation, which typically lasts about 1 rein, are used to recover vertical profiles of atmospheric refractivity from about 60 km in altitude downward, Pressure and temperature profiles follow from use of the gas law and the assumption of hydrostatic equilibrium. GPS/MET, we believe, will provide sub-Kelvin temperature accuracies from the tropopause up to an altitude of -40 km with better than 1 km vertical resolution (Fig. 10). Such information, if it were ongoing and obtained globally, could contribute significantly to the study of global climate change. Below the tropopause water vapor sharply limits the accuracy of temperature and pressure recovery; however, nominal profiles for temperature and pressure, particularly over tropical ocean regions, enable one to recover information on water vapor distribution to aid in the study of thermal energy transport and short term weather forecasting,

Although radio occultation techniques have been used to probe planetary atmospheres for over three decades, the unique aspect in this case is the use of small and relatively low cost space systems to carry out the measurement programs. For example, this mission uses a Pegasus-launched microsat built by Orbital Sciences Corporation for another flight experiment. The GPS flight receiver to be carried piggy-back is a ruggedized version of the TurboRogue receiver (Meehan et al., 1992), which is a commercial receiver developed by JPL for high precision ground applications, including the global network used for TOPEX/Poseidon, geodynamics and crustal deformation studies, and Earth rotation monitoring. To keep costs low, only commercial parts are used in the flight version of the TurboRogue, increasing the attendant risk. The planned mission duration of the

GPS/MET phase is only a few months at best and it is intended as a demonstration of the scientific potential of a GPS-based radio occultation system.

Other Missions. In addition to the missions cited above there are others, such as TOPEX Follow-on, Gravity Probe-B and STEP for relativity, and last but not least, the EOS series, which could benefit both scientifically and operationally from GPS.

CONCLUSIONS

The success of the GPS experiment on TOPEX/Poseidon has unequivocally demonstrated the scientific potential of GPS-based tracking for future LEO remote sensing missions, In some cases, such as gravity recovery and atmospheric limb sounding, GPS will itself serve as a remote sensing system, in addition to fulfilling its usual navigation role. While the GPS advantage for missions like TOPSAT and TOPEX Follow-on is evident, the full implications go deeper. GPS will enable a new class of low-cost and low-orbit altimetry missions, Because GPS-based POD accuracy is largely insensitive to orbital altitude over the range of 300 to 3000 km (Fig. 8), the orbital altitude of future altimetry missions may be substantially lowered to save mission costs without incurring POD penalties. Precise tracking at lower altitudes allows the use of low-power, solid-state, dual-band altimeters. For a given precision, the required altimeter-radiated power varies as the fourth power of altitude. Lower power enables smaller solar arrays on smaller satellites that are launched by smaller launch vehicles. Altimetry missions like TOPEX Follow-on, and EOS ALT can therefore be significantly cheaper because of GPS.

ACKNOWLEDGMENTS

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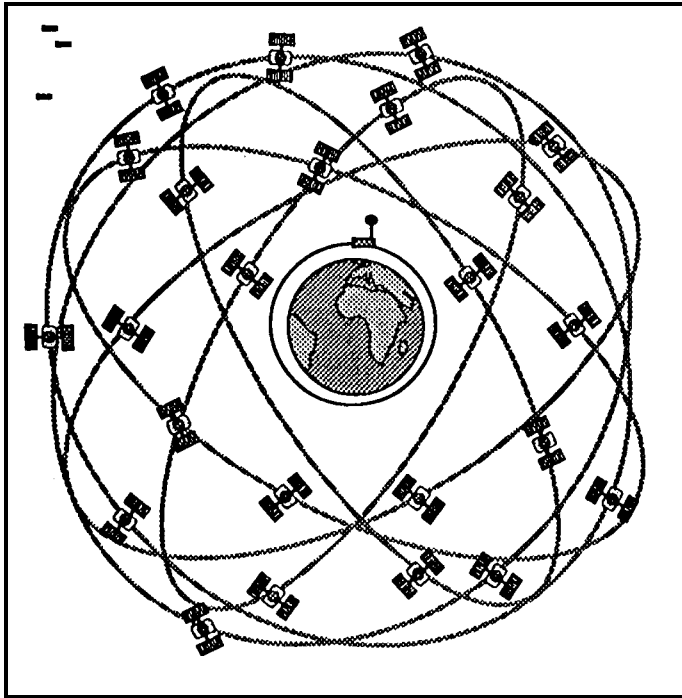
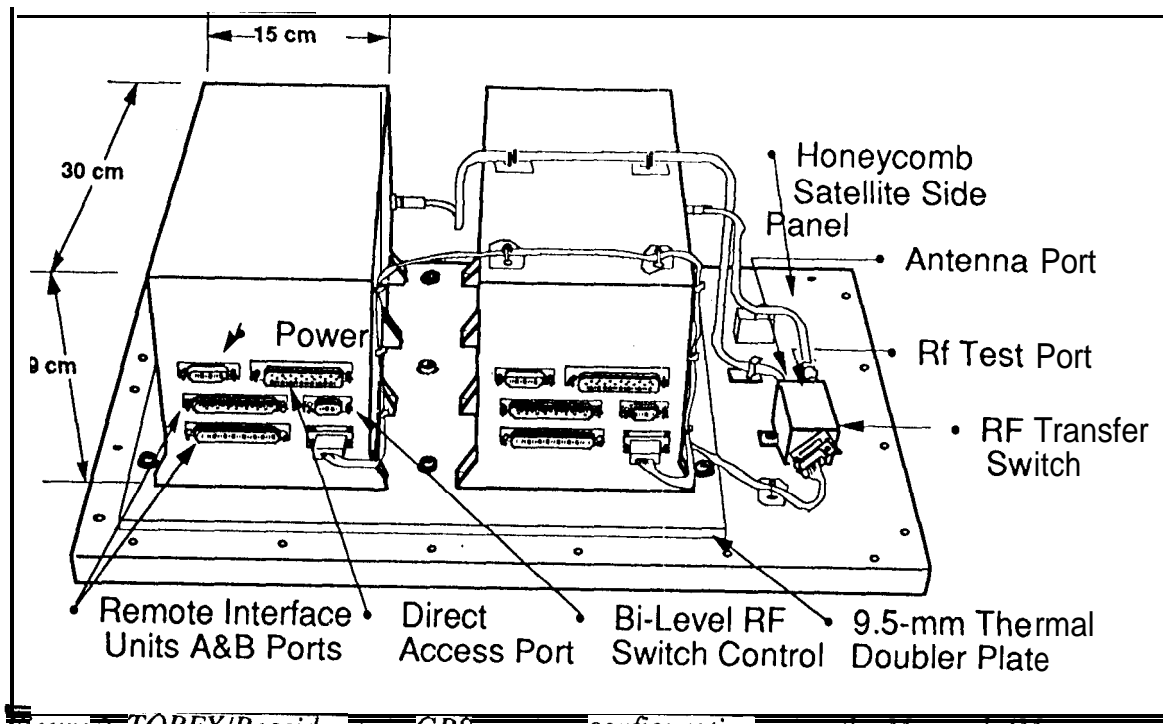'igure 1.   GPS constellation with LEO user.

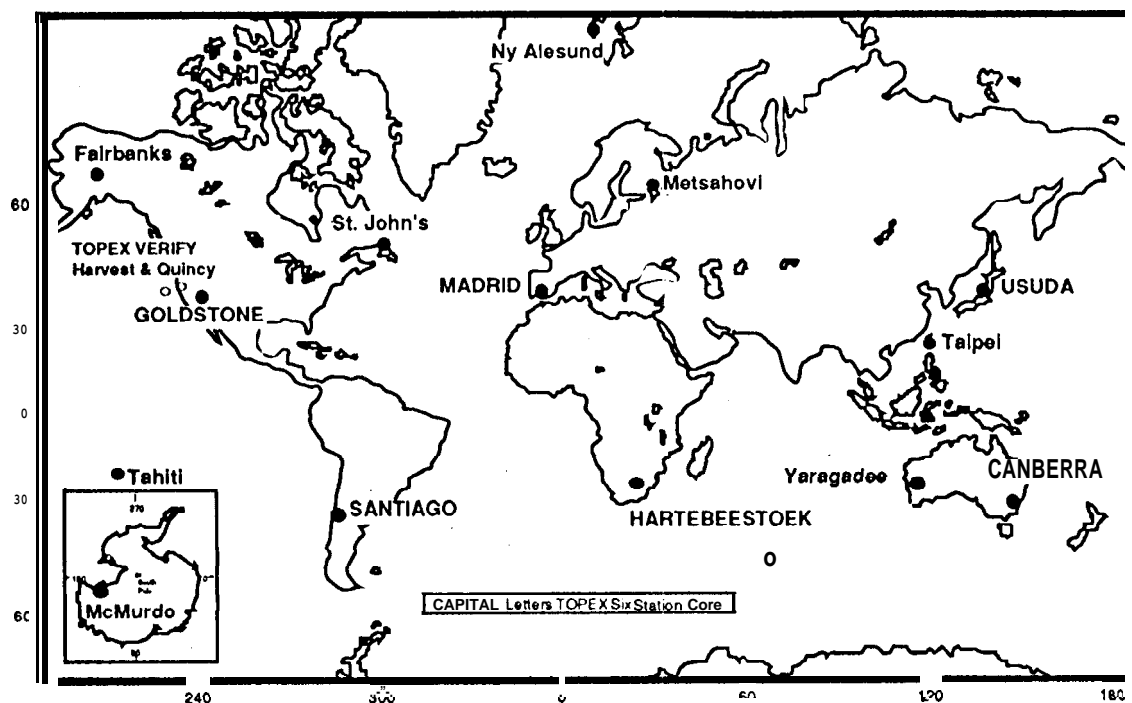*Figure 2, TOPEX/Poseidon twin GPS receiver configuration using the Monarch 'M.*

*Figure 3. GPS global tracking network for TOPEX/Poseidon.
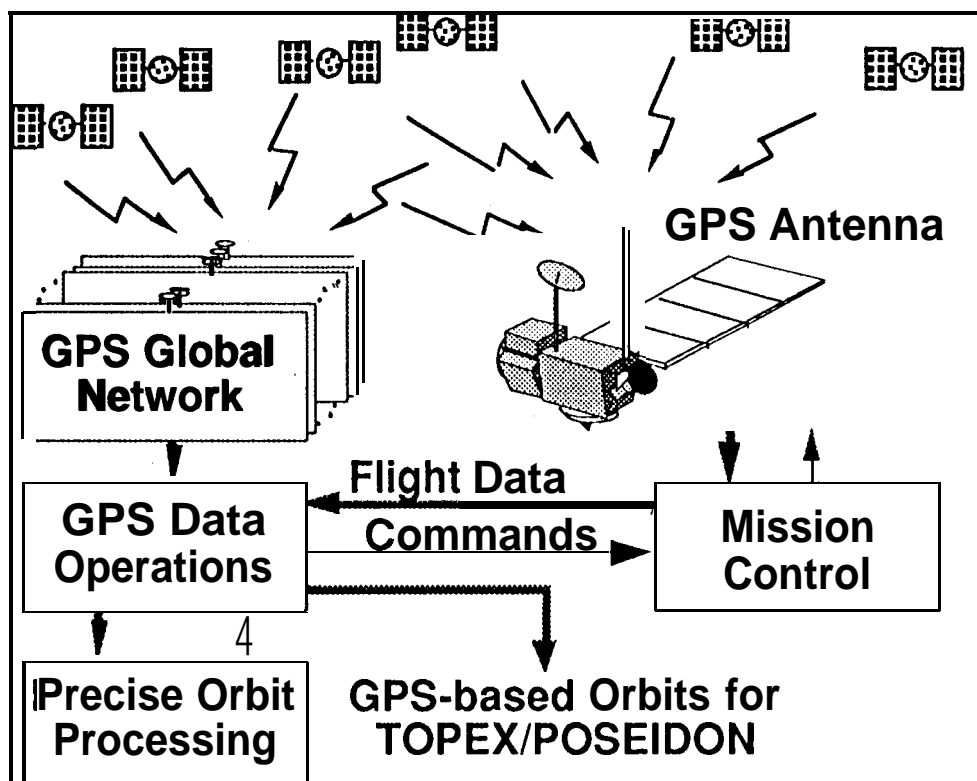Stations are part of IGS network for Geodynamics.*

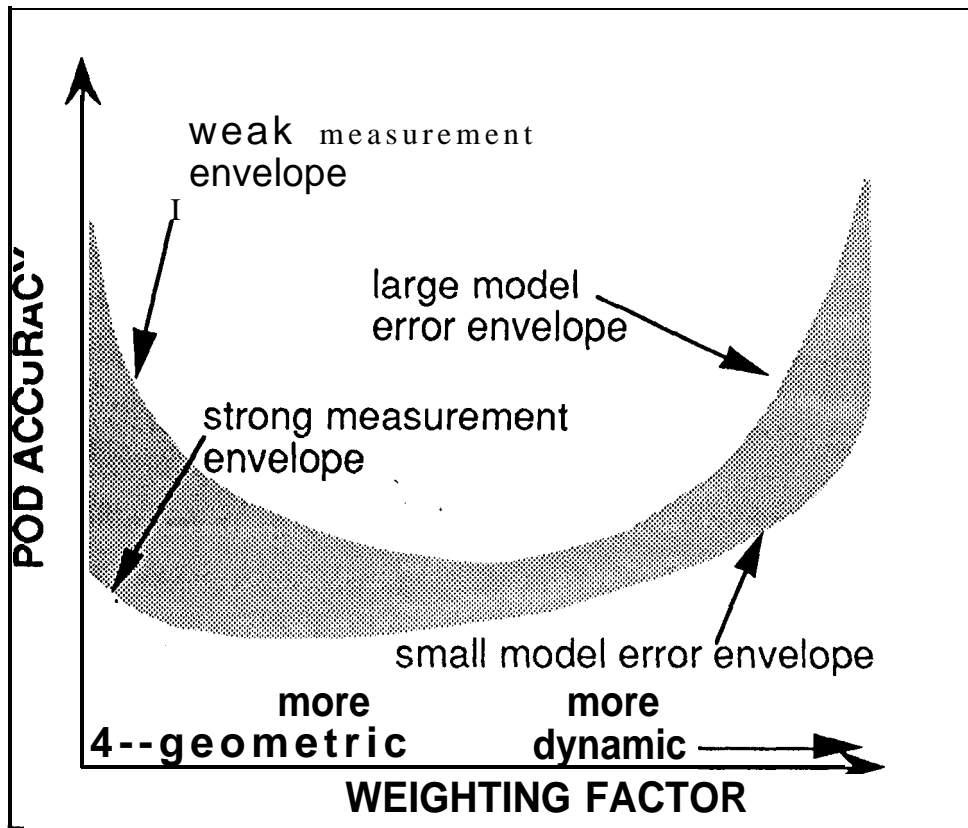*gure* 4. *Tracking System for GPS-based POD on TOPEX/Poseidon.*

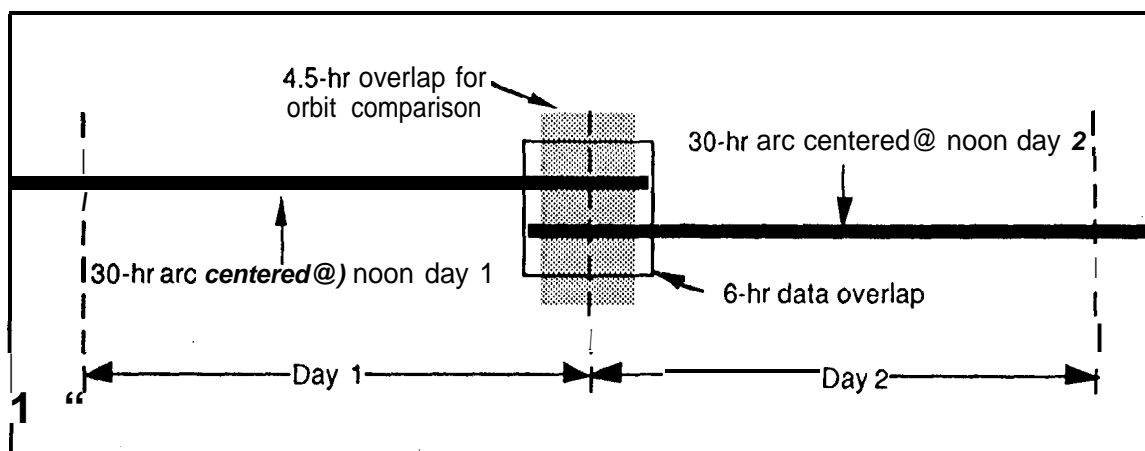*Figure 5. Performance Index: Reduced Dynamic POD*

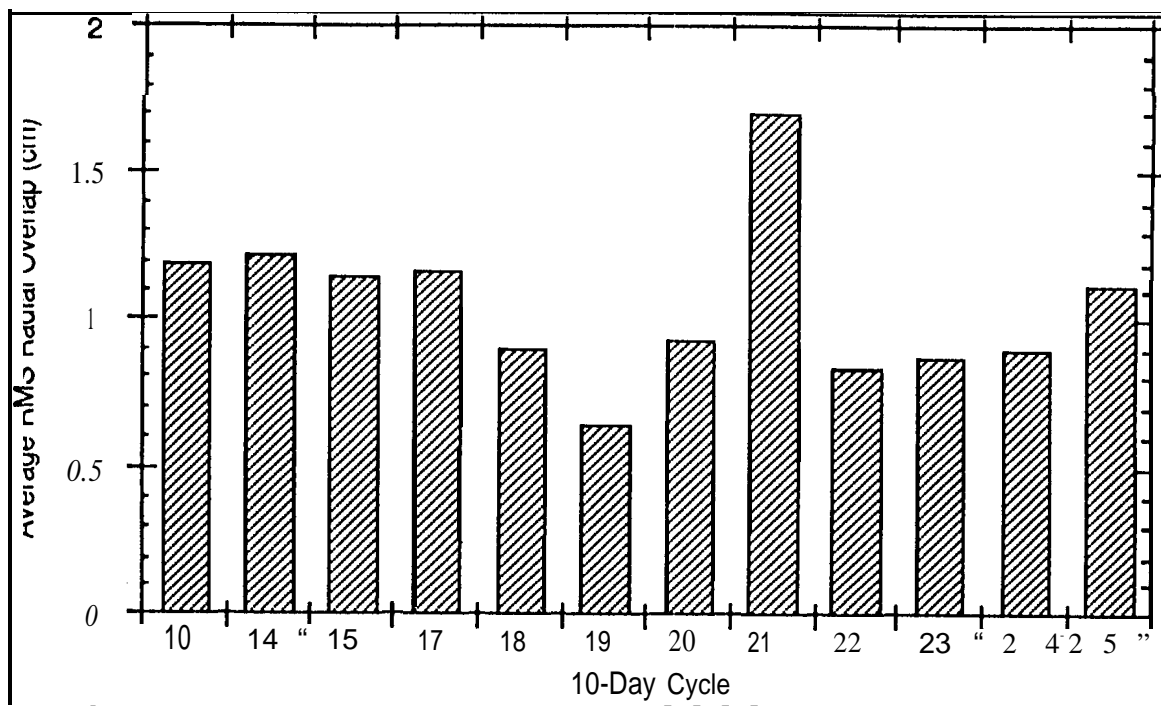*Figure 6. Overlap zone for comparison of POD solutions.*

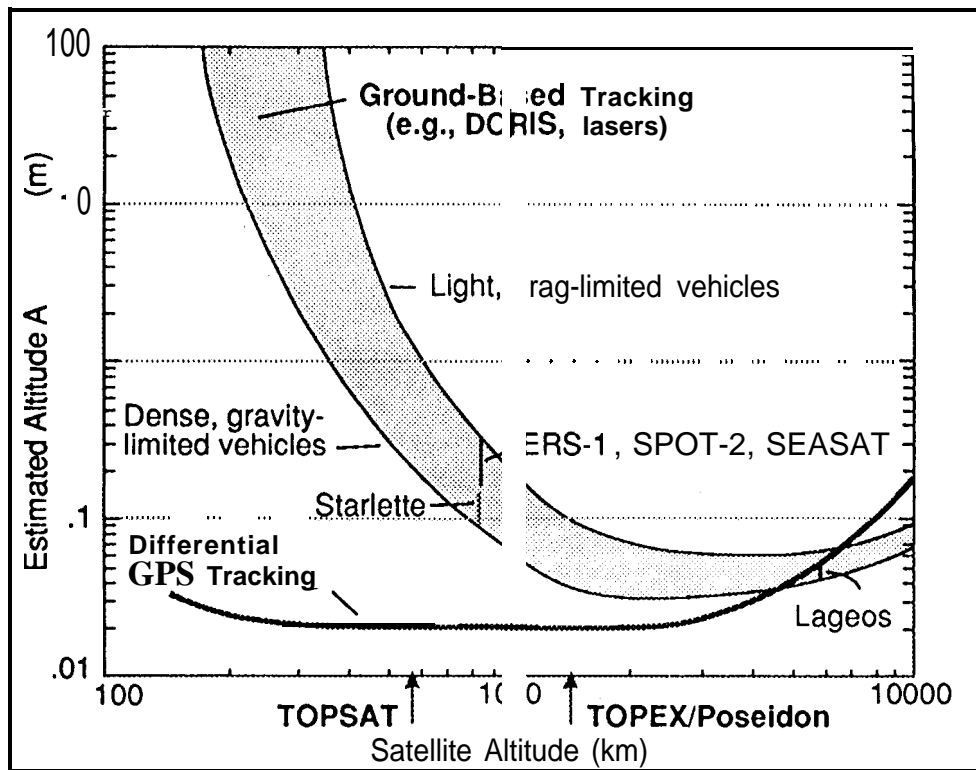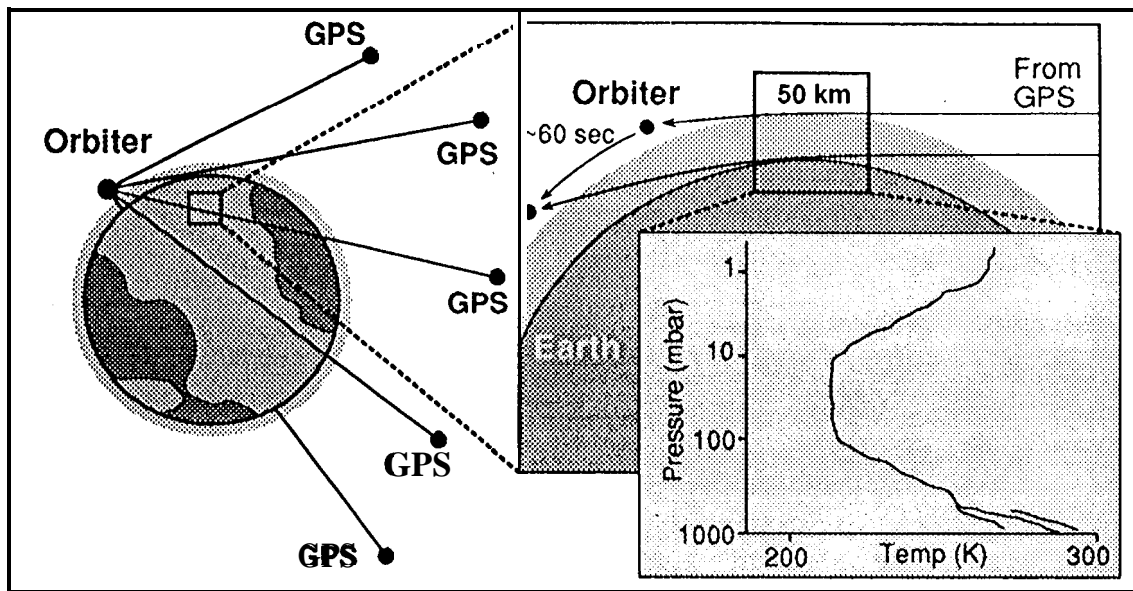Figure 7. Overlap agreement with reduced dynamic POD: February-July, 1993

gure 8. *Estimated POD accuracy versus orbit altitude,*

igure 9. Schematic of the satellite-to-satellite geometry for probing the atmosphere of tl Earth using the radio occultation technique.
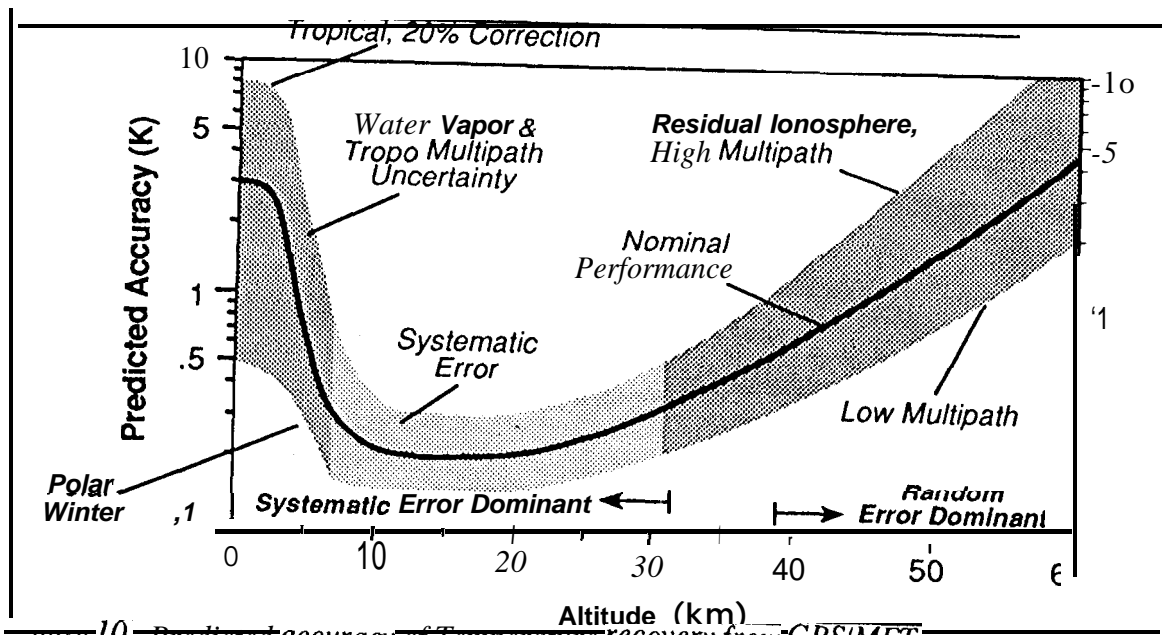
Figure 10. Predicted accuracy of Temperature recovery from GPS/MET.